A Swedish Grouting Design Concept: Decision Method for Hard Rock Tunneling

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ABSTRACT: Efficient grouting of hard rock requires adequate knowledge of the water-bearing fracture system in the rock mass. The observational method approach involves identifying different possible scenarios and relating them to predefined strategies for grouting design. Parameters useful in preparing a relevant description of the rock mass are presented, as well as a method for choosing a conceptual model. The implications of different fracture systems for the grouting design are discussed. A method is presented for deciding whether grouting is needed in order to ensure a high degree of probability that tunnel leakage will remain below the inflow requirements. The methods presented are applied to data from a real tunnel to illustrate the procedures.

INTRODUCTION

Pre-grouting is a common method employed to reduce water leakage into rock tunnels. In hard rock, the water leaks into the tunnel through the fracture system in the rock mass. Water flow behaves differently in different fracture systems and the grouting design should be adapted to current conditions. By doing so, the grouting resources can be used where they are needed – it may be unnecessary to grout certain tunnel sections while other sections may need special treatment. An adaptive grouting principle requires some form of verification that the desired results have been achieved and that performance is satisfactory. A formal design approach that incorporates the idea of proposing adapted designs and then verifying them with observations is known as “the observational method”. The grouting principle suggested in this paper follows the ideas outlined in the observational method.

The aim of the grouting design is to keep water leakage into the finished tunnel below the inflow requirements specified for the tunnel. This inflow cannot be measured during tunnel construction, hence some other method needs to be used to assess whether conditions will be met. A decision must be made at the tunnel front whether to grout or to proceed with excavation. A decision method to answer this question, based on data from water pressure tests in a small number of boreholes.

This work is a part of research collaboration dealing with rock grouting in Sweden.

Objectives and limitations

The purpose of this work is to establish a relevant description of the fractured rock mass based on appropriate parameters, and to condense this into simple tools developed for tunnel construction. The description includes the representation of the rock mass by means of a conceptual model, a method for calculating an inflow prognosis, and a method suitable for making tunnel front grouting decisions.

The aim of the decision method described is to seal tunnels to achieve the set total inflow requirement. The methods are recommended for crystalline rock types.

THE OBSERVATIONAL METHOD

A design concept known as the "observational method" was adapted early on for soil mechanics (Peck 1969) to offer a structured method for handling design situations based on uncertain data and models. The idea is to consider predicted system behavior in relation to an initial design proposal. Based on data obtained from observations during construction, it is then possible to carry out verification or modification of the design as the actual conditions are revealed. The observational method is now included as a design principle in the European standard (Eurocode) for geotechnical design (EN 1997-1:2005).

The use of the observational method has been explored mainly for rock stability design, although it is also suitable (but not yet defined) for grouting. At the early stages, before grouting, the observational method stipulates characterization of the ground conditions and assessment of the ground behavior, assessing both the most likely behavior and possible deviations. Appropriate sealing measures should then be proposed, including prediction of their result and selection of parameters to be observed. By establishing the possible ground behaviors and pre-defined grouting strategies to account for these behaviors, both performance and efficiency can be approved.

THE TASS TUNNEL

The TASS tunnel was chosen as an example to illustrate the methods presented. It was constructed in 2007-2009 by the Swedish Nuclear Fuel and Waste Management Company (SKB) (Emmelin and Funehag 2010), as a part of SKB's research facility, Äspö HRL, in southeast Sweden. TASS is 80 m long, almost horizontal, strikes NE-SW, and is located at a depth of 450 m in granitic rock. The inflow requirement was 1 l/min per 60 m tunnel. Fig. 1 shows the layout of the grouting fans.

A base design for grouting was made, specifying the design parameters. The geometric parameters were: distance between grouting boreholes, length of fans and overlap of fans. Grout (silica sol or a low pH cement grout) was chosen according to predefined alternatives, based on the hydraulic aperture b of the fractures intersecting the grouting boreholes. Other grouting design parameters, such as silica sol gelling time, grouting overpressure and further control holes or grouting boreholes, were set to vary depending on other predefined conditions.

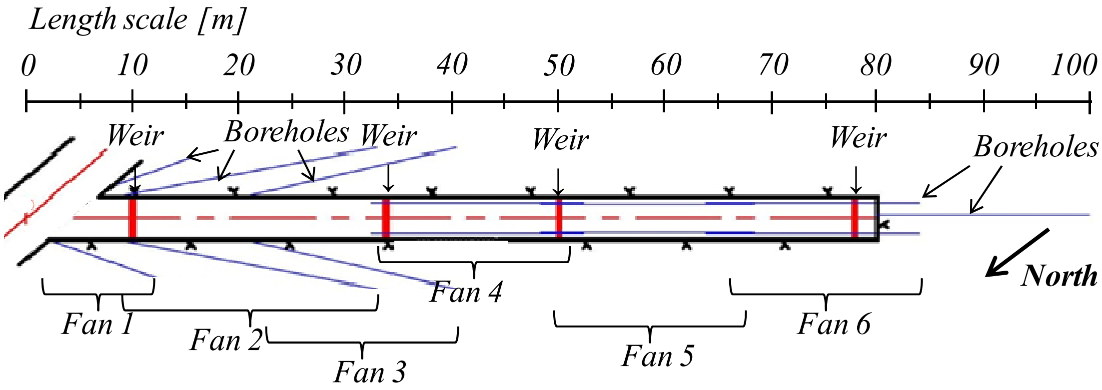

FIG. 1: The TASS tunnel and the geometry of the grouting fans.

THE ROCK MASS – PARAMETERS AND CONCEPTUAL MODEL

When grouting fractured hard rock for tunnel construction, knowledge of the relevant properties of the tunnel rock mass is important. As hard rock can *per se* be regarded as impermeable (for the purposes of this work), it is the fracture system that is of interest. An effective way of describing this is to use a conceptual model of the rock mass. A conceptual model is a set of assumptions used to describe a system for a given purpose.

The permeability of rock mass thus depends on the fracture system. Fracture systems can take the form of sparsely connected fractures, well-connected fracture networks and fracture zones, see Fig. 2. Fracture zones may or may not include a fault core. Only fracture zones without a dominating fault core are addressed here.

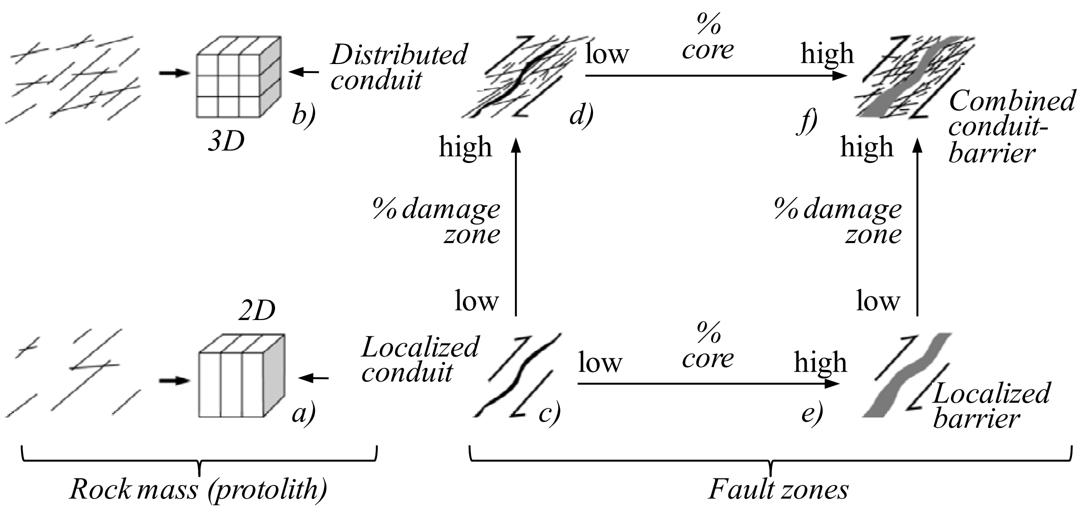

FIG. 2: Conceptual scheme of fracture systems in rock mass (left) (modified after Fransson and Hernqvist 2010), and in fault zones (right) (modified after Caine et al 1996). a) 2D system, b) 3D system, c) and d) fracture zones without and with a damage zone, e) and f) fault zones with a fault core

Implications for grouting – predefined options

The approach includes using predefined strategies for the different conceptual models of the water-bearing fracture system. For rock mass with a 2D fracture system (one dominating water-bearing fracture set) and a tunnel oriented perpendicular to the fracture set selective grouting is recommended. Only sections with fractures that need to be sealed should be grouted. Sealing the conductive fractures should result in an inflow reduction in line with target values. For sections where hydraulic tests show the rock mass is sufficiently tight, no grouting is needed (Emmelin et al. 2004).

For rock mass with a 3D fracture system (two or more water-bearing fracture sets) systematic grouting is often preferable. Since there are many flow paths, it is not sufficient to focus purely on the most conductive fractures. If only those fractures are sealed, there is a risk that water will find other ways into the tunnel, commonly referred to as "moving the water leakage" from one tunnel section to a neighboring section.

When the tunnel intersects a fracture zone, the focus should be on sealing this zone. The fracture zone may act as a backbone, supplying water to connecting fractures, and sealing the fracture zone efficiently may also limit the inflow into neighboring fractures (Emmelin et al. 2004, Fransson and Hernqvist 2010).

Parameters for a rock mass conceptual model relevant for grouting design

According to the observational method the behavior of the most likely rock mass, and of possibly occurring rock mass, should be described. A functional set of parameters is proposed below. They can be used to choose a conceptual model for the water-bearing fracture system and thus provide a base for grouting design.

The hydraulic head h

The hydraulic head is the force that makes fractures transmit water. h is necessary to calculate the hydraulic apertures, for deciding the grouting pressure, and for tunnel inflow predictions. A rough estimation of h is the depth below the ground (given a shallow groundwater level).

Hydraulic aperture b

b is calculated from the transmissivity T via the cubic law, $T = \rho g b^3/12\mu$, where T is the transmissivity [m^2/s], ρ is the density of water [kg/m^3], g is the gravitational acceleration [m/s^2] and μ is the viscosity of water [Pa·s] (Snow 1968). Since different grouts have different abilities to enter and penetrate fractures, the choice of grout should be based on the apertures of the fracture that needs to be sealed (Fransson et al. 2012). Grouting time and pressure and borehole spacing should also be chosen to achieve the necessary penetration length in the fractures.

Fracture frequency

There are several fracture intensity parameters for quantifying the amount of fractures in rock (Dershowitz and Herda 1992). A functional parameter is the fracture frequency P_{10} , the number of fractures per meter along a borehole or a scan-line. A change in P_{10} indicates that the fracture system in the rock mass changes. A P_{10} increase is a sign of the existence of a fracture zone, which should be grouted differently compared to the surrounding rock mass.

Orientations and number of fracture sets

The number of water-bearing fracture sets influences the connectivity of the fracture system. The major fracture sets are identified using a stereo plot. With one dominating water-bearing fracture set, most fractures are close to parallel and the rock mass resembles Fig. 3 a). The fractures are not very well-connected and neither water nor grout spreads between fractures to any great extent. With two or more water-bearing fracture sets, the rock mass resembles Fig. 3 b), a connected fracture system. Such system is demanding to grout. After a fracture has been sealed, water could find other paths into the tunnel.

The grouting boreholes should be oriented at an angle, which gives a high probability of intersecting the water-bearing fractures.

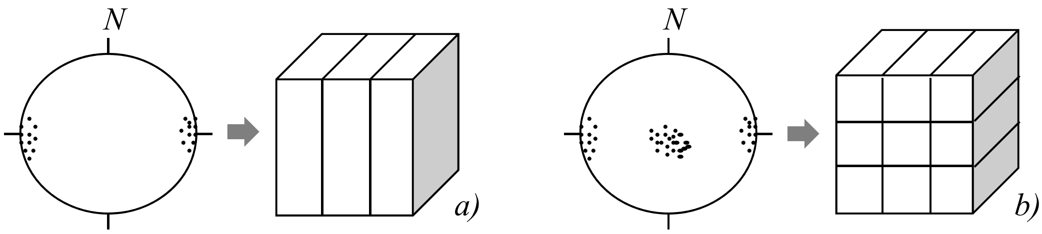

FIG. 3: Interpretation of stereo-plots of open fractures, assumed here to be water-bearing. a) and b) correspond to Fig. 2.

Flow dimension D_q

Flow dimension is important to both water leakage and grout spread.

The flow pattern *within* a fracture influences the flow dimension, as illustrated in Fig. 4. D_q is evaluated from pressure build-up tests (Doe and Geier 1990) or from grouting data (Gustafson and Stille 2005). With large contact areas, water flow can be channeled, D_q = 1D, while with large open areas the flow is radial, D_q = 2D.

A fracture with 2D flow is relatively easy to intersect with a borehole and inject with grout. However, with a fracture with 1D flow it is unlikely that the boreholes will intersect the flow channels. A sparse 1D network is thus difficult to grout.

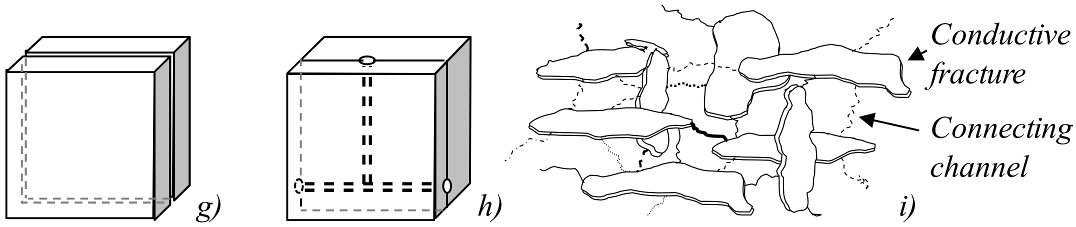

FIG. 4: Conceptual models of flow within a fracture. g) Fracture with 2D flow, h) flow along channels within the fracture (1D flow), i) combination of 2D fractures and 1D flow channels (after Gustafson et al. 2008)

Example TASS: parameters and conceptual model

An existing set of pre-investigation data (Hardenby et al. 2008), obtained from three cored boreholes drilled along the planned tunnel length, were used to assess the design parameters. Hydraulic tests in sections of these holes resulted in estimations of b along the length, and of h. P_{10} was achieved from core mappings, and fracture orientations from BIPS (Borehole Image Processing System). D_q for the dominating structures was calculated from a hydraulic test in a probe hole.

The interpretation of the test results demonstrated that the rock mass has one dominating fracture set, close to vertical and oriented approximately perpendicular to the tunnel. There are also some fractures with other orientations connecting the fracture system. At about 20 m along the tunnel length a fracture zone was identified both by increased P_{10} and by a peak in water inflow. Relating back to Fig. 2, most of the tunnel rock mass consists of 2D rock mass (a), intersected by a fracture zone characterized somewhere between localized conduit (c) and distributed conduit (d). The fracture zone has fractures with b of up to 100 – 200 μm, while the surrounding rock mass has fractures of up to 50 μm. h is 320 m. D_q is 2D. If 1D flow was also present, this information would be obscured by the 2D behavior of the fracture zone.

INFLOW PROGNOSIS

An inflow prognosis based on Hawkins (1956) can be made using Eq. 1. This can be used in two ways. In an early stage, the inflow requirement q_A stated for the tunnel can be inserted to calculate the necessary maximum transmissivity of the grouted rock, T_{gr}. T_{gr} is used to assess how fine-aperture fractures need to be sealed to achieve the inflow requirement. The second way of using the equation is after grouting – when the achieved T_{gr} can be measured – to calculate a prediction of the tunnel inflow.

$$q = \frac{2\pi \cdot T_0 \cdot H / L}{\ln\left(\frac{2H}{r_t}\right) + \left(\frac{T_0}{T_{gr}} - 1\right) \cdot \ln\left(1 + \frac{t}{r_t}\right) + \xi} \tag{1}$$

where q = calculated inflow of water per length unit of the tunnel [m^3/s per m], T_0 = transmissivity of the ungrouted rock mass section [m^2/s], T_{gr} = transmissivity of the grouted zone surrounding the tunnel section [m^2/s], H = resting groundwater head [m], L = length of the tunnel section [m], r_t = tunnel radius [m], t = thickness of the grouted zone surrounding the tunnel [m], and ξ = skin factor [-].

Example TASS: inflow prognosis

For TASS, Eq. 1 was used to calculate b of the finest fracture that needed to be sealed. The inflow requirement Q_A = 1 l/min per 60 m was used together with the geometrical parameters H = 320 m, L = 80 m, r_t = 2.5 m, t = 5 m (reasonable for the fans outside the tunnel contour but probably an overestimation for the fans inside the tunnel contour), the skin factor $\xi = 5$, and $T_0 = 2.3 \cdot 10^{-6}$ m^2/s. The transmissivity of the grouted zone satisfying the equation was then found to be $T_{gr} \approx 1.0 \cdot 10^{-8}$ m^2/s. This represents the total transmissivity of all ungrouted fractures. On the assumption of independent flow in the fractures (2D), T_{gr} is the sum of T for all ungrouted fractures. The data can be represented with adequate accuracy by means of a Pareto distribution with 195 fractures (as mapped in the cored boreholes). Setting the sum of the T-values for the smallest fractures at $1.0 \cdot 10^{-8}$ m^2/s, the largest of the fractures has $b = 10$ µm (Funehag 2008). Based on this, the aim of the grouting design was set at sealing fractures down to $b = 10$ µm with sufficient penetration, 1.5 m, which would create the desired overlap of grout from neighboring grouting boreholes.

AT THE TUNNEL FRONT

Following the concepts outlined in the description of the observational method, it is necessary to reveal whether the current situation is acceptable or if action needs to be taken. At the tunnel front, this involves deciding whether the tunnel section needs (further) grouting or not, before excavation proceeds.

The decision method

The decision method is based on statistical analysis of hydraulic tests of a small number of boreholes, and is derived in Gustafson et al. (2010).

A critical allowed transmissivity, T_A, based on the inflow requirement for the tunnel section covered by the fan is calculated before the analysis starts. The critical values are calculated slightly differently depending on whether the rock mass is ungrouted, or if some grouting has already been performed in the section.

The calculation of the critical value in the ungrouted rock mass is based on Eq. 1. Without a grouted zone $T_{gr} = T_0$, so the middle term in the denominator equals zero. If ξ is set at zero and q is set at the permitted inflow q_A for the tunnel section, then T_A is calculated as

$$T_A \approx \frac{\ln(2H/r_t)}{2\pi} \cdot \frac{L_t}{H} \cdot q_A \tag{2}$$

The critical value in the grouted rock mass is calculated based on Eq. 1, using $t \approx r_t$, Matheron's conjecture (Matheron 1967) and the assumption that the transmissivities can be described using a lognormal distribution. $T_{A,gr}$ is then calculated as

$$T_{A,gr} \approx \frac{L_t}{2\pi H} \cdot q_A \tag{3}$$

A small number, N, of water pressure tests in tunnel front boreholes each result in a transmissivity value estimated using the specific capacity, $T \approx Q/dh$, where Q = the measured flow during the test, and dh = the overpressure applied during the test. These are compared to the precalculated T_{crit}. The outcome of the test is n^+, the number of observations for which $T \geq T_{crit}$. The combination of N and n^+ results in a *confidence level*, presented in Table 1, that the *median transmissivity* of the rock volume section is smaller than T_{crit}. The confidence levels equal one minus the accumulated binomial function of (n^+; N; ½).

TABLE 1: The confidence level that the median transmissivity of the rock section is smaller than T_{crit}, when n^+ out of N tested boreholes result in $T \geq T_{crit}$.

↓N n^+→	0	1	2	3	4	5
1	0.5	0	-	-	-	-
2	0.75	0.25	0	-	-	-
3	0.88	0.50	0.13	0	-	-
4	0.94	0.69	0.31	0.06	0	-
5	0.97	0.81	0.50	0.19	0.03	0
6	0.98	0.89	0.66	0.34	0.11	0.02
7	0.99	0.94	0.77	0.50	0.23	0.06

Example TASS: The decision method

The six grouting fans in TASS are shown in Fig. 1 (Funehag 2008). Before grouting, each section was tested with water pressure tests in three to four front holes used as probe holes. After final grouting, each section was tested in five to seven control holes. The inflow requirement was 1 l/min per 60 m tunnel, which equals $q_A = 2.8 \cdot 10^{-7}$ m³/(s·m).

The critical value in the ungrouted rock mass is calculated at $T_A = 1.9 \cdot 10^{-7}$ m²/s using Eq. 2, and the critical value in the grouted rock mass is calculated at $T_{A,gr} = 3.4 \cdot 10^{-9}$ m²/s using Eq. 3.

For each fan the outcome of the comparisons of the hydraulic tests before grouting with the precalculated T_A is summarized in Fig. 5 a). The outcome of the comparisons of the hydraulic tests after grouting with the precalculated $T_{A,gr}$ is summarized in Fig. 5 b).

Fan 2 is used as an example: Before grouting, $N = 4$ and $n^+ = 4$ result in a confidence level of 0 (Table 1), hence it needed grouting. In Fig. 5 c) this is visualized as all four test results before grouting (the squares) are larger than T_A. After grouting of Fan 2, $N = 7$ and $n^+ = 3$ result in a confidence level of 0.50 of the inflow staying below the set requirement. In Fig. 5 c) three of the seven control hole test results (the triangles) are larger than $T_{A,gr}$.

a) Before grouting	*N*	n^+	conf. level
Fan 2	4	4	0.00
Fan 3	4	3	0.06
Fan 4	3	2	0.13
Fan 5	4	3	0.06
Fan 6	4	3	0.06

b) After grouting	*N*	n^+	conf. level
Fan 2	7	3	0.50
Fan 3	7	1	0.94
Fan 4	5	0	0.97
Fan 5	5	0	0.97
Fan 6	6	0	0.98

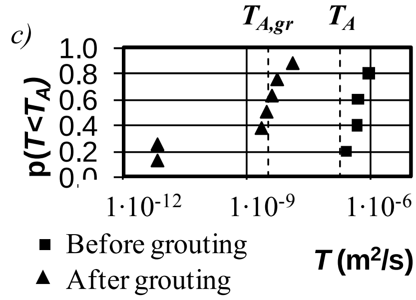

FIG. 5: The result of the decision method for the TASS tunnel for a) the ungrouted and b) the grouted rock mass. c) The T-values from Fan 2.

The low confidence levels before grouting of all fans indicate that pregrouting was needed for all. Fans 2 to 6 were all grouted.

Fans 3 to 6 show very high confidence levels that grouting was successful.

The inflow was measured in weirs in the finished tunnel. The total inflow was found to remain below the inflow requirement. The Fan 4 section leakage was too large; the positioning of the control holes led to failure of the decision method to identify the leakage. A condition for the decision method is that the control holes are located in the sealed zone.

CONCLUSIONS

To achieve a grouting design for a tunnel, it is recommended that investigations be carried out to describe the rock mass in a way that is appropriate for grouting. Important parameters that have been identified are the hydraulic head, h, the hydraulic aperture, b, the fracture frequency, P_{10}, the number and orientation of fracture sets, and the flow dimension, D_q. A useful way of describing the water-bearing fracture system is to choose a suitable conceptual model and to allow this to influence the grouting design.

A decision method to help make decisions on whether or not a section needs to be grouted is presented. The method is based on hydraulic tests in a small number of boreholes, which are compared to a precalculated value with the inflow requirement as input data. This results in a prediction with a chosen confidence level that the leakage into the tunnel section will remain below the requirement.

The methodology described here was applied to data from the TASS tunnel.

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